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Effects of OASIS® Phenolic Foam on Hydraulic Behaviour of Permeable Pavement Systems

Abstract

Sustainable drainage is a major challenge for highway and environmental agencies to mitigate flooding and understand the optimum design parameters of pavement structure. This paper experiments the hydraulic properties of OASIS® phenolic foam material examining infiltration rate and steady-state behaviour, water storage capacity of different thicknesses of OASIS® material, and the effect of OASIS® material in deferring the water peak flow during rainfall intensities of 100mm/hr, 243mm/hr, 400mm/hr, and 563mm/hr. This paper designs an application programme that estimates the optimal thickness of OASIS® layer to retain 100% of stormwater for a duration of 15 minutes. The results from laboratory tests corroborate the performance efficiency of OASIS® material to delay peak stormwater flow and mitigate flooding. The OASIS® materials not only increase the ability of permeable pavement system to absorb and retain stormwater up to a saturation limit but also retain the nutrient contaminants infiltrate to groundwater. The designed application programme will help the designers and constructors to increases the drainage efficiency of pavement structure by estimating the optimal thickness of OASIS® layer required to delay peak stormwater flow during maximum rainfall intensities.

Keywords: stormwater; permeable pavement system; geotextile material; infiltration rate; optimal thickness

1. Introduction

Impermeable pavement surfaces increase the volume of stormwater runoff that overburdens the capacity of drainage networks and eventually causing floods particularly in urban areas [1]. Sustainable drainage system (SuDS) is a contemporary challenge that considers permeable pavement system (PPS) as the environmentally and economically beneficial approach for minimising flood risks [2,3]. Application of PPS as a SuDS method implements source control, prevention, detention, infiltration and biodegradation techniques (Woods-Ballard et al., 2007). The retention of excessive stormwater at the PPS layers minimises the flooding risks and can be used for irrigation needs after removing pollutants (Nnadi, 2009, 2014; Wilson et al., 2004).

Two decades ago, there was no specific design for PPS in the United Kingdom (UK) as PPS constructions were rare, but it is now regularly used in parking lots, compounds, and residential areas (Wilson et al., 2004). The most common design for PPS in the UK is a geotextile layer beneath the surface layer because geotextile materials retain stormwater pollutants and enhance the process of biodegradation within permeable pavement (Newman et al., 2011; Wilson et al., 2004; Nnadi 2009). The geotextile material is provided to separate backing geotextile layers from sand/aggregate bedding layers and aggregate or geocellular sub-base (Wilson et al., 2004). Several materials such as polyethylene, polypropylene and polyester are used to manufacture the geotextile layer but there is no scientific evidence on compromising attenuation and filtration attributes (Nnadi et al. 2014; Wilson et al., 2004). The three-dimensional structure of OASIS® phenolic foam characterised by highly porous cells that increase the material ability to absorb and attain stormwater up to a saturation limit. Yong et al. (2008) observed that geotextile layer increased the probability of voids clogging affecting the total performance of PPS. Nnadi (2009) observed the performance of PPS with a geotextile layer composed of Inbitex Composite® and silts, and identified that geotextile layer improved the filtering and attenuating stormwater. Lowe et al. (2010) invented a 3D structure module that contains phenolic foam material for irrigation and filtering system purposes. Nnadi et al. (2014) studied the hydraulic properties of OASIS® material with 1.3 cm and 2 cm thicknesses under rainfall intensities of 100 mm/ hr, 200 mm/hr and 400 mm/hr and determined the positive performance of PPS for retaining stormwater within the pavement structure. Nnadi et al. (2014) identified that one-centimetre increase in OASIS material would increase its stormwater storage capacity by 37%. However, the experimental results by Nnadi et al. (2014) require to be validated by different thicknesses of OASIS® material subjected to different rainfall intensities.

This paper experiments the hydraulic properties of OASIS® material examining infiltration rate and steady-state behaviour, water storage capacity of different thicknesses of OASIS® material, and the effect of OASIS® material in deferring the water peak flow during rainfall intensities of 100mm/hr, 243mm/hr, 400mm/hr, and 563mm/hr. This paper designs an application programme that estimates the optimal thickness of OASIS® layer to retain 100% of stormwater for a duration of 15 mins.

2.Experimental Methodology

2.1 Test rigs design

The control rig was designed with 250 mm sub-base, 50 mm base, and 100 mm paver layers without a geotextile layer. The control rig was replicated three times under each rainfall intensity attaining the required time for initial infiltration rate, and constant rate of water flow. Three rigs were designed with 15 mm, 25 mm, and 35 mm thicknesses of OASIS® material (Figure 1). A 5-mm diameter hole was made at the bottom of rig to drain out the water. To simulate the rainfall event, water was flowed evenly through a funnel connected with a sprinkler for a duration of 15 mins over the surface of PPS model. The process was replicated three times for four maximum rainfall intensities. The same type of bucket was used but without a hole in the base to prevent water drainage outside the bucket and study the likelihood of flooding during 15 mins of rainfall intensities.

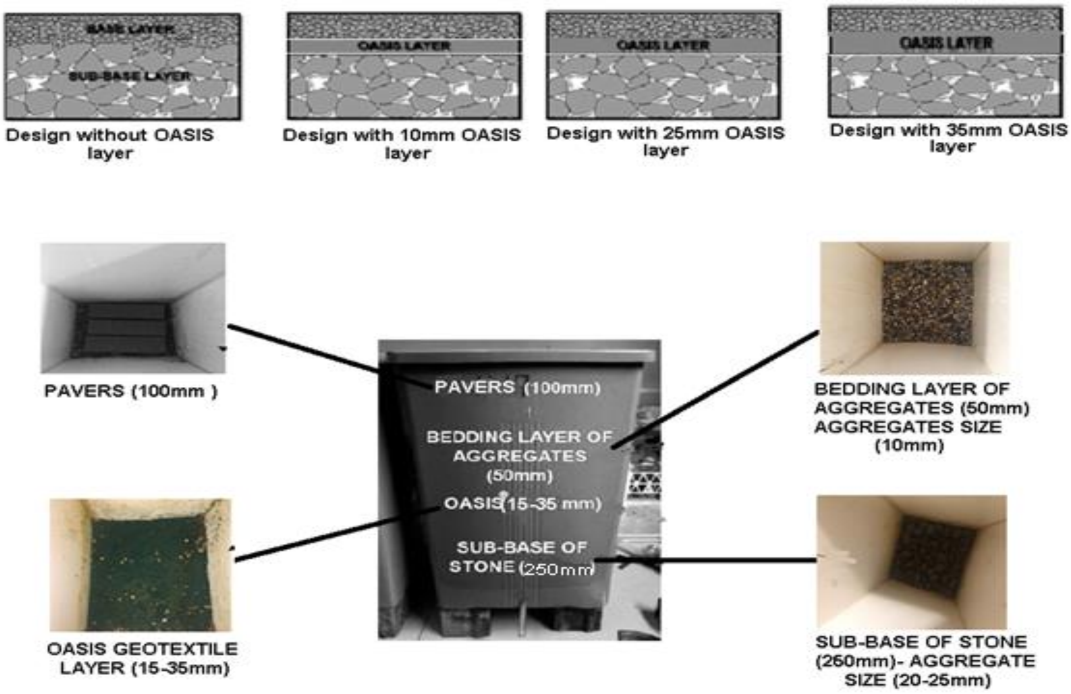


Figure 1: Scheme of the control and OASIS® rigs

2.2 Extreme rainfall intensity analysis

To study the hydraulic properties of the OASIS® material, four extreme rainfall intensities were chosen for different cities. Maximum rainfall intensities were selected within the range of 100mm/hr to 600mm/hr that correspond to a 100-year return period for a duration of 15 mins. The 15-mins rainfall duration was determined based on the required time to reach the steady-state stage of control rigs. Four extreme rainfall intensities were chosen such as 100 mm/hr (London, UK), 243 mm/hr (Kuala lumpur, Malaysia), 400 mm/hr (Yongchun, China) and 563mm/hr Auckland, New Zealand) (Figure 2). The final infiltration rate, the required time for water drain rate became zero, was measured after 24 hours to determine the stormwater storage capacity of OASIS® material.

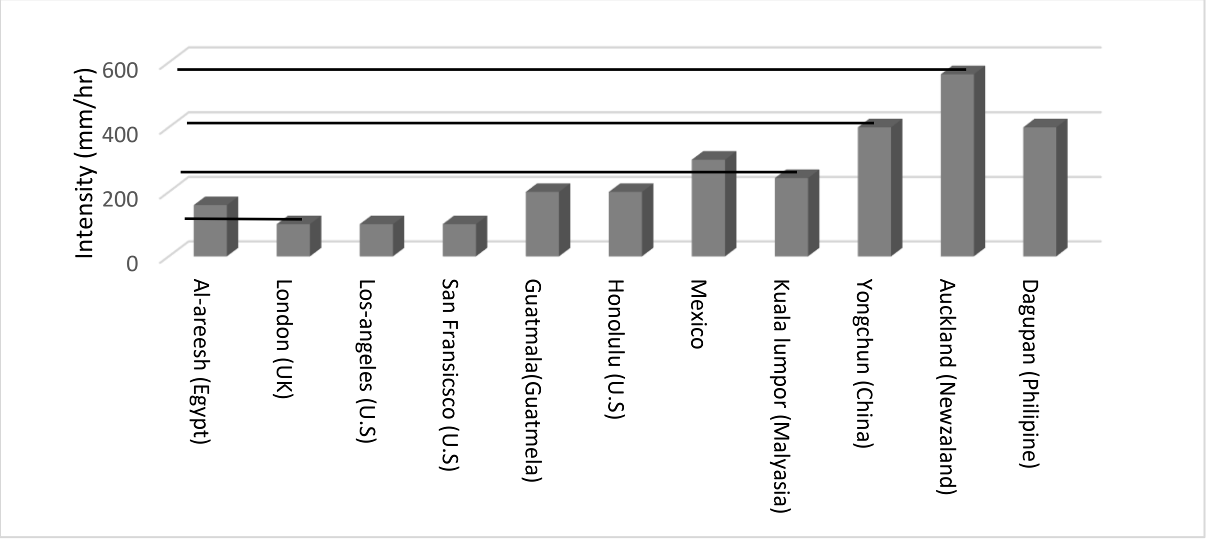


Figure 2: Maximum rainfall intensities for different cities with 100-year return period for 15 mins. (Campos-Aranda, 2010; UNESCO, 2008)

2.3 Simulation of rainfall event

The portable laboratory rainmaker (PLR) was used to simulate extreme rainfall intensities (Figure 3). Tests carried out by the PLR, to resemble rainfall events showed high accuracy in simulating rainfall intensity ranging between 50 to 450 mm/hr for a duration less than 30 minutes (Barrera et al., 2008). However, Nnadi et al. (2014) believe that a water loss of 20% occurred when the rainfall event exceeded 15 minutes. To overcome this problem, the equivalent volume of water for rainfall intensity was distributed over the surface area of test rig per minute. For example, rainfall intensities of 100mm/hr, 243mm/hr, 400mm/hr, and 563mm/hr were equal to 150ml/min, 364ml/min, 600ml/min, and 845 ml/min, respectively. A container was added below the base level of the test rig to accumulate the water drained through the provided hose and measured the water volume per minute.

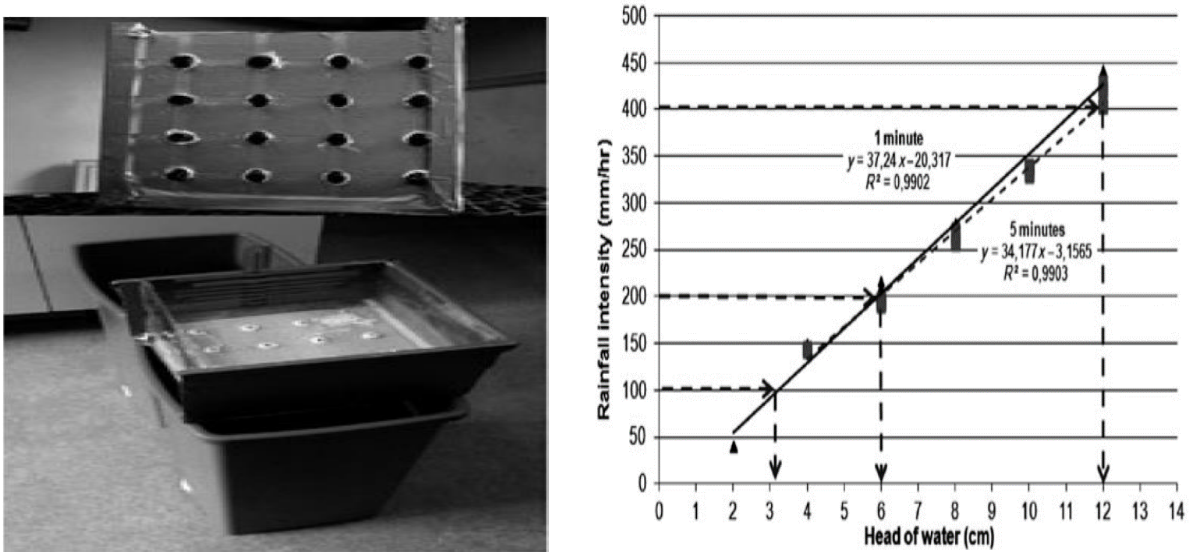


Figure 3: Portable laboratory rainmaker (PLR) image (a) and calibration line (b) (Barrera et al., 2008; Nnadi et al., 2014)

Experimental tests were carried out on the designed rigs based on three primary determinants. The first factor is the initial infiltration rate, the required time for water to flow out through the provided hose. The comparison between the initial infiltration rate of the control rigs (PPS model without OASIS® layer) and PPS models with the OASIS® layer helped to assess the material impact on delaying the water's peak flow. The second factor is the required time for water to flow out at an approximately constant rate known as the steady-state stage. The hydraulic behaviour analysis was carried out at two phases: the necessary time taken to reach the initial infiltration rate and the moment when the water flowed out to approach the steady-state stage. The sum of initial infiltration time and steady-state stage moment determined the duration of a rainfall event. Subsequently, rainfall duration was simulated under extreme rainfall intensity for London and other cities across the world. The period of rainfall event was considered enough to study the infiltration behaviour and achieve the comparison between PPS models. The last factor was defined by the final infiltration rate, as the required time for water drain rate become zero.

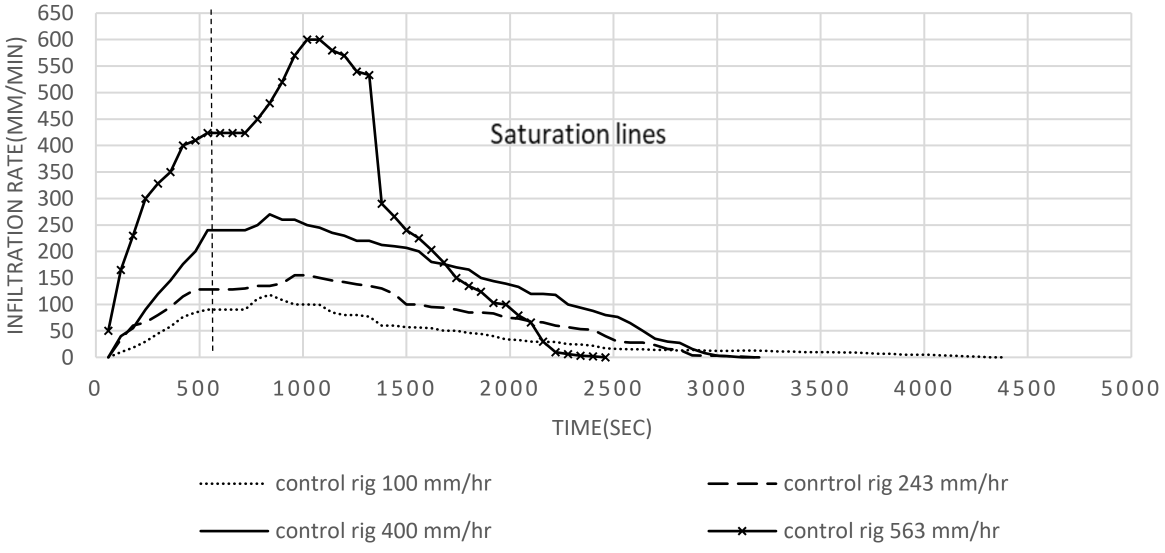
3. Results and discussion

3.1 Performance of OASIS® material on stormwater flow

The average rates of initial infiltration were calculated to study hydraulic behaviour of pavement layers at control rigs. Figure 4 (a) demonstrates the time required to infiltrate through pipe and to reach a steady-state stage for the control rigs. Initial infiltration began at 110 seconds for a rainfall intensity of 100mm/hr, while infiltration was strated at 40 seconds for 563 mm/hr rainfall intensity (Figure 4(a), Table 1). The time required to reach the steady-state stage at control rig was estimated between 9 and 10 mins. (Table 1). The results support the findings of other studies that estimated the timing of steady-state stage at 10 mins. (Davies et al., 2002; Rodriguez-Hernandez et al., 2012, 2013; Castro-Fresno et al., 2013). The results also support the chosen duration of 15 mins. rainfall to compare the attenuation behaviour of control rigs and design rigs with OASIS® layer.

Figures 4(a), (b), (c) and (d) illustrate the infiltration behaviour of control rigs and PPS model with 15mm, 25mm and 35mm thicknesses of OASIS® material, respectively. The average initial infiltration rate was 1.35 mins. for the design of control rig (Figure 4(a) and Table 1) while 3.55 mins. for 15mm thickness of OASIS® layer (Figure 4(b) and Table 1). The average initial infiltration rates for design rigs with 25 mm and 35 mm thicknesses of OASIS® material were 5.54 mins. and 7.13 mins., respectively (Figure 4(c) and 4(d); Table 1). These results support the findings of Coupe et al. (2014) that OASIS® material defers the peak flow by storing water, act as a slow replenish of PPS resoriver layer during heavy rainfall events allowing enough time to drain out stormwater through provided pipe and eventually mitigates the adverse effects of flooding.

It was observed that the OASIS® material significantly increased the attenuation of peak flow by absorbing water. For example, 35-mm thickness OASIS® material delayed peak flow of water by 97%, 50%, 37%, and 27% for 100mm/hr, 243mm/hr, 400mm/hr, and 563mm/hr rainfall intensities, respectively (Table1). It was observed that a 35-mm thickness of OASIS® layer could absorb approximately one entire rainfall event of 100mm/hr.



4(a)

4(b)

4(c)

4(d)

Figure 4: Infiltration rates and timing to reach steady –state stage during experiments a) control rigs, (b) 15 mm OASIS®, (c)25 mm OASIS® and (d) 35 mm OASIS® layers

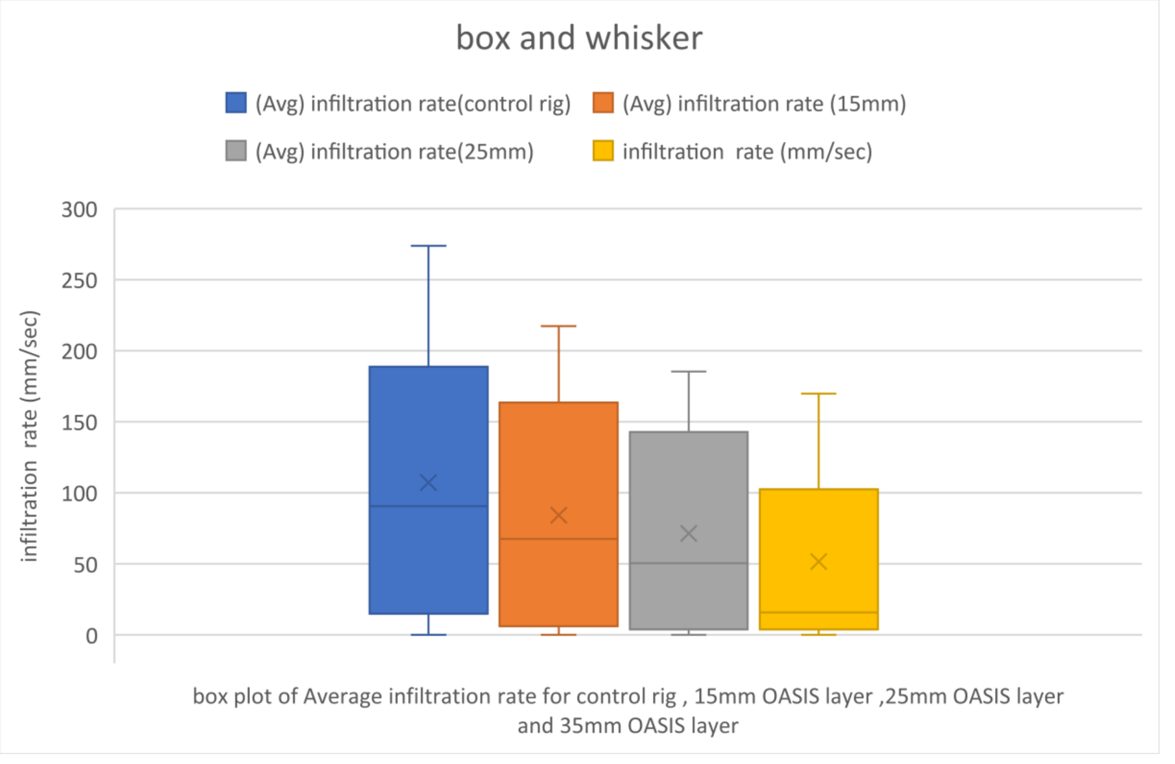


Figure 5: box and whisker statistical analysis for control rigs and design rigs with OASIS® material thickness of 15mm, 25mm and 35mm

Figure 5 shows the Box and whisker statistical analysis of infiltration rates for control rig and OASIS® samples. Maximum infiltration rate was around 270mm/sec in sample without OASIS® layer while the infiltration rate of PPS model with 35mm OASIS® layer thickness was approximately 170mm/sec. It is observed that the interquartile range of infiltration rates for model with 35mm thickness is smaller meaning the infiltration rates is more consistent around the median than the infiltration rates for control rigs. Figure 5 reveals the significance of OASIS® layer in reducing rainwater infiltration rates by retaining water inside its structure.

Table 1: Average time to reach infiltration and steady-state stage for control rigs and design rigs with OASIS® materials thickness of 15 mm, 25mm and 35 mm

Rainfall intensity mm/hr	control rigs		Design rigs (OASIS® materials thickness)					
			15 mm		25 mm		35 mm	
	initial infltration (min)	steady state (min)	initial infltration (min)	steady state (min)	initial infltration (min)	steady state (min)	initial infltration (min)	steady state (min)
100	1.8	10	6	20	10	25	14.5	31
243	1.5	8	3	16	5.5	22	7.5	24
400	1.33	10	2.8	15	3.67	19	5.5	21
563	0.67	9	2.4	14	3	16	4	20

The time to reach the steady-state stage was the moment when the OASIS® layer was fully saturated and the infiltration rate was constant (Table 1). The diameter of stormwater pipe can be significantly reduced by using OASIS® material in PPS as the volume of drain out is less comparing to that of control rigs resulting in less construction and maintenance costs of PPS.The infiltration behaviour of OASIS® material reveals three zones of performance: absorption (A), absorption and infiltration (B) and infiltration (C) zones (Figure 6). The performance of OASIS® material at zone C seems to be same as control rig (Figure 6). The water storage capacity of OASIS® layer was estimated for three performance zones. For example, the average storage capacity in absorption zone (A) was 1,701 ml (15 l/m²), 2,467 ml (23 l/m²), and 3,201 ml (32 l/m²) and 24-hours storage capacity was 1,977 ml (18 l/m²), 2,716 ml (26 l/m²), and 3,642 ml (34 l/m²) for OASIS® layers with thickness of 15 mm, 25 mm and 35 mm, respectively (Table 2). However, OASIS® material has similar performance on the water storage capacity of PPS regardless of time period in absorption zone (A). For instance, the proportions of water storage during the infiltration zone (A) and after 24-hours were 26% and 32% for the OASIS® with 15 mm thickness under rainfall intensity of 100 mm/hr, respectively (Table 3). The experimental tests reveal that a 10-mm increase of OASIS® layer thickness can increase the water storage capacity by 12% in PPS (Table 4). The storage capacity of OASIS® material dropped by two-third comparing to the results of Nnadi et al. (2014) that might be due to enhancement added to the material commercially available.

Park et al. (2013) designed the PPS model based on the parameters (such as rainfall intensity, duration of rainfall event, aggregate size and base, sub-base and pavers layer thicknesses) of hydraulic behaviour of PPS that are approximately similar to the parameters used in this study. Park et al 2013 experimented the water storage capacity of PPS as 34.84 (l/m²) while this study identifies that average water storage capacity of 35mm OASIS® thickness is 34 (l/m²) with under 100 mm/hr rainfall intensity. The comparison justifies the water retention ability of OASIS® material in the PPS.

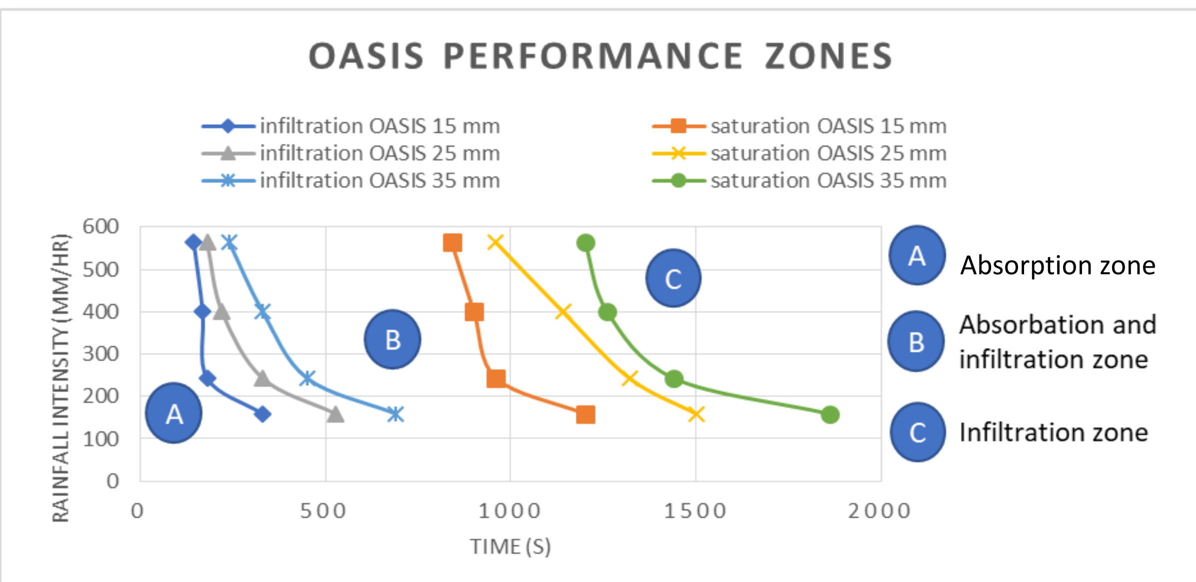


Figure 6: Performance zones of OASIS® material with different thickness (15mm, 25mm and 35 mm) corresponding to 100-year return period of rainfall for 15 mins. duration

Table 2: Average and 24-hours water storage capacity of OASIS® layer during absorption zone (A)

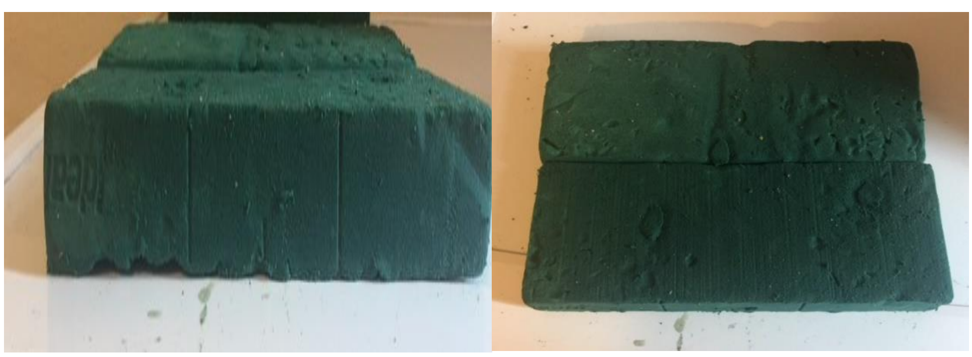
volume of stored water by millilitre in PPS model						
performance zones	OASIS thicknesses (mm)	159 mm/hr	243 mm/hr	400 mm/hr	563 mm/hr	Average storage (ml)
(A) Absorption zone	15	1656.31	1431.08	1827.48	1881.53	1701.35
	25	2422.07	2331.98	2530.18	2602.25	2467.12
	35	3061.71	3052.70	3322.97	3368.02	3201.35
total stored water in OASIS layer	15	1956.00	1996.00	2007.00	2007.00	1977.25
	25	2615.50	2694.00	2761.00	2761.00	2716.40
	35	3391.00	3493.00	3459.00	3459.00	3462.00

Table 3: Water retention percentage in OASIS® layer during different rainfall intensities used in the experiment

Percentage of volume stored water in OASIS®					
performance zones	OASIS thicknesses (mm)	159 mm/hr	243 mm/hr	400 mm/hr	563 mm/hr
Absorption zone (A)	15	46%	26%	20%	15%
	25	68%	43%	28%	21%
	35	86%	56%	37%	27%
total stored water in OASIS layer	15	75%	36%	21%	16%
	25	87%	48%	33%	28%
	35	99%	60%	45%	40%

The purpose of constructed PPS models was to assess the efficiency of OASIS® material with different thicknesses for mitigating flooding under maximum rainfall intensities. The results indicated an outstanding capability of PPS models with different thicknesses of OASIS® layers, as no flooding occurred up to the rainfall intensity of 563 mm/hr during 15-mins test period; however, flooding was observed with rainfall intensities over 600mm/hr. The structural strength of OASIS® materials was examined after the experiments and it was revealed that OASIS® materials had adequate strength to bear static loads (bedding layers and paver's weights) without compressing or squeezing (Figure 7). However, pavement surface is subjected to both the dynamic traffic loads and static loads; future studies require to experiment the structural strength of OASIS® materials under dynamic traffic loads.

(a)Before



(b) After

Figure 7: OASIS® material before and after the test completion

4. Develop a computer-based application design for optimal thickness of OASIS® layers

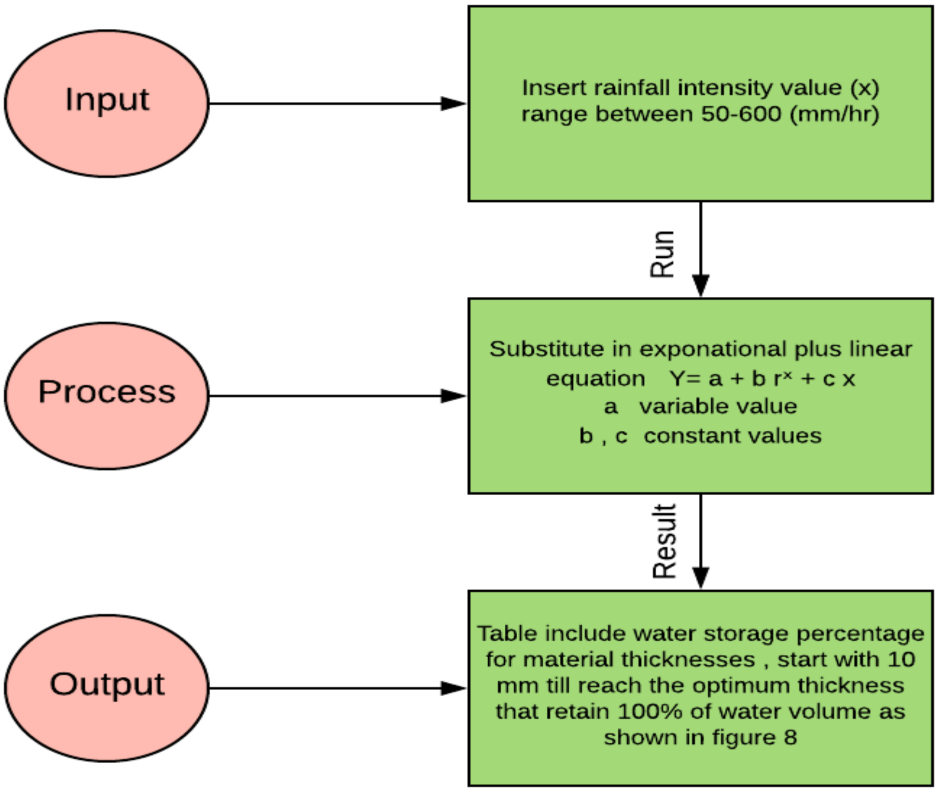
A computer-based application programme was designed for determining the optimal thickness of OASIS® materials to retain 100% stormwater under maximum rainfall intensities for 15-mins durations. This application will help the PPS designers and constructors to identify the optimal thickness of OASIS® layer required to delay peak flow during storms. Understanding the volume of stormwater in OASIS® layer in PPS can increases the design efficiency and confidence. The results from laboratory tests on OASIS® layer thicknesses, rainfall intensities and stormwater storage capacity were analysed and designed by curve fitting software and programming language. The fitted curves for four categories of rainfall intensities were developed to simulate the stormwater retention capacity of different thicknesses of OASIS® materials (Table 4)

Table 4: Percentage of stormwater retention in OASIS® layers for rainfall intensities

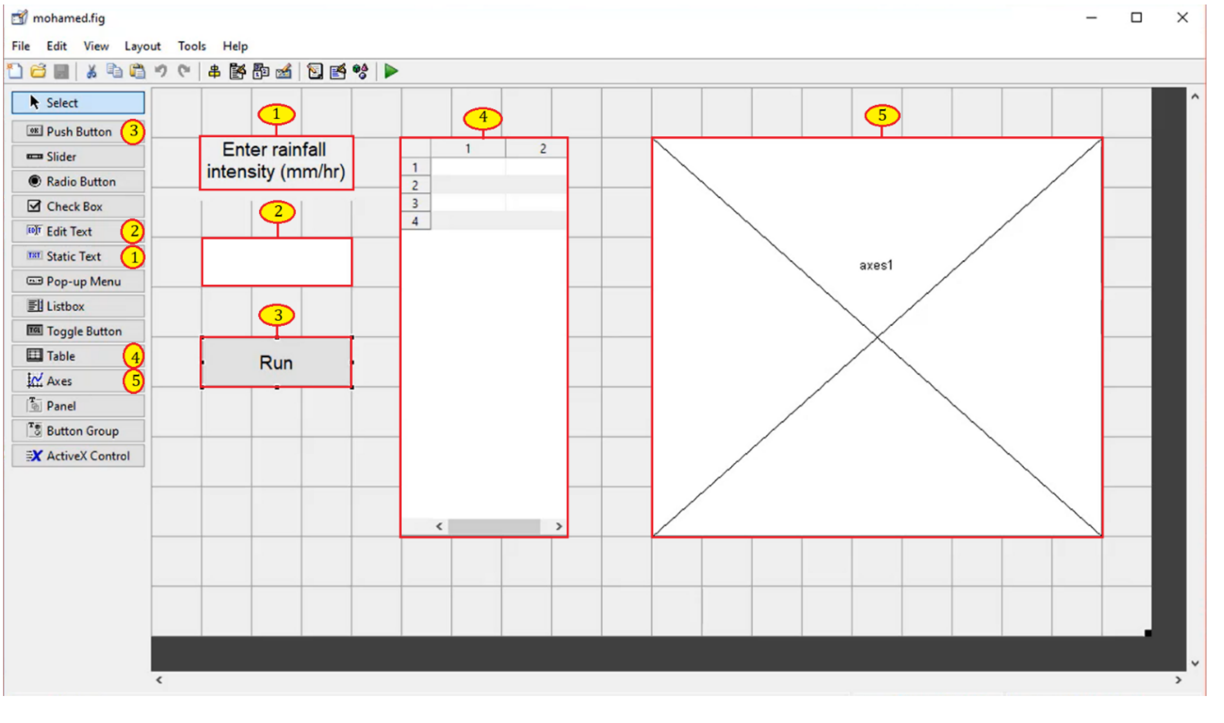
Thickness (mm)	100 mm/hr	243 mm/hr	400 mm/hr	563 mm/hr
10	69%	31%	16%	10%
15	75%	37%	22%	16%
20	81%	43%	28%	22%
25	87%	49%	34%	28%
30	93%	55%	40%	34%
35	99%	61%	46%	40%
40	106%	67%	52%	46%
45	111%	73%	58%	52%
50	117%	79%	64%	58%

55	123%	85%	70%	64%
60	129%	91%	76%	70%
65	135%	97%	82%	76%
70	141%	103%	88%	82%
75	147%	109%	94%	88%
80	153%	115%	100%	94%
85	159%	121%	106%	100%
90	165%	127%	112%	106%
95	171%	133%	118%	112%
100	177%	139%	124%	118%

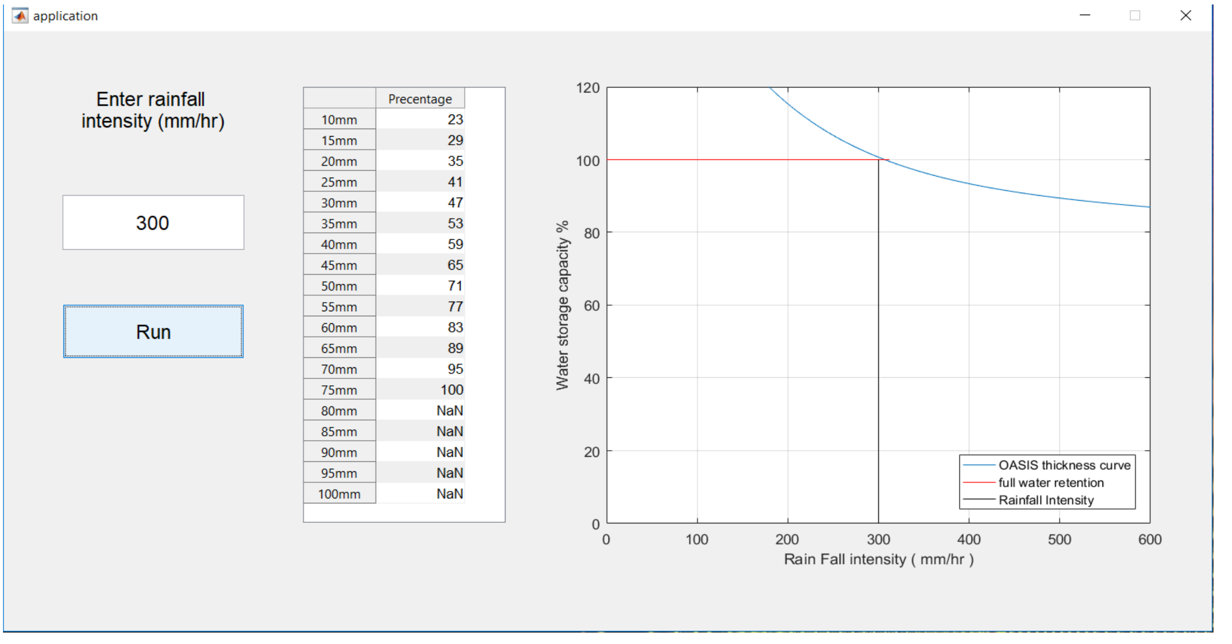
The functions developed from the fitted curves were used to develop an application design tool for optimal thickness of OASIS® layers in the PPS (Figure 8). Figure 8(a) describes the operation of application model to approach the optimum thickness of OASIS® to store 100% of water during rainfall event. To run this application, the maximum rainfall intensity (mm/hr) for a specific city was inserted in text box no.2 and press the button no. 3 to run the application as shown in Figure 8(b). Figure 8(c) presents a table including the retained water percentage for each thickness until reaching the required thickness to retain 100% storage capacity. After setting up the application design, the optimal thickness of OASIS® layers in PPS was calculated for different rainfall intensities (Figure 8(c)). For example, a 75-mm thickness of OASIS® layer is required in the PPS to retain 100% of stormwater during rainfall intensity of 300mm/hr (Figure 8(c)).



(a) Application mechanism diagram



(b) Operational window



(c) Result window

Figure 8: MATLAB code to design the optimal thickness of OASIS® material

5. Conclusions

Sustainable drainage for the strategic road network is a major challenge for the highway agencies to mitigate the flooding and optimum design parameters to assist designers in designing the pavement structure. Lack of understanding the drainage performance of pavement structure risks inefficient design and the possibility of ground water contamination, flooding through under-design and inefficient use of resources through over-design. The geotextile materials are used in the PPS to retain stormwater pollutants and enhance the process of biodegradation within permeable pavement and eventual reduce flooding. This paper experiments the hydraulic properties of OASIS® material examining infiltration rate and steady-state behaviour, water storage capacity of different thicknesses of OASIS® material, and the effect of OASIS® material in deferring the water peak flow during rainfall intensities of 100mm/hr, 243mm/hr, 400mm/hr, and 563mm/hr.

The results from laboratory tests show that the initial infiltration rates were 110 seconds and 40 seconds for rainfall intensities of 100 mm/hr and 563 mm/hr for control rigs without the OASIS® material, respectively. The OASIS® material significantly increased the attenuation of peak flow by absorbing water. For example, 35-mm thickness of OASIS® material delayed peak flow of water by 97%, 50%, 37%, and 27% for 100mm/hr, 243mm/hr, 400mm/hr, and 563mm/hr rainfall intensities, respectively. It was observed that a 35-mm thickness of OASIS® layer could absorb approximately one entire rainfall event of 100mm/hr for 15-mins duration and a 10-mm increase of OASIS® layer thickness can increase the water storage capacity by 12% in the PPS. This paper designs an application programme that estimates the optimal thickness of OASIS® layer to retain 100% of stormwater for a duration of 15 mins.

Pavement surface is subjected to both the dynamic traffic loads and static loads; future studies require to experiment the structural strength of OASIS® materials under dynamic traffic loads. The techniques to maintain the OASIS® layer in the PPS avoiding material clogging, application feasibility of OASIS® materials on strategic road network and pollution performance efficiency of OASIS® materials require to be studied in future.

References

1. Campos–Aranda D.F. (2010). Rainfall Maximum Intensities for Urban Hydrological Design in Mexican Republic. *Ingeniería, investigación y tecnología* 11(2), 179-188. http://www.scielo.org.mx/pdf/iit/v11n2/v11n2a5.pdf
2. Castro-Fresno, D., Andrés-Valeri, V. C., Sañudo-Fontaneda, L. A., Rodriguez-Hernandez, J. (2013). Sustainable Drainage Practices in Spain, Specially Focused on Pervious Pavements, *Water* 5(1), 67-93. doi:10.3390/w5010067
3. Davies, J.W., Pratt, C.J., and Scott, M.A., 2002. Laboratory study of permeable pavement system to support hydraulic modeling. *Proceedings of the 9th international conference on urban drainage (9ICUD)* Portland, Oregon, 8–13 September.

4. Lowe, T., Shuttleworth, A., Culleton, P. and Puehmeier, T. (2010). Structural modules with absorbent elements for drainage and irrigation. Permavoid Limited (Monton House Monton Green, Manchester M30 9LE, GB) [online] (EP2198093). Available from <http://www.freepatentsonline.com/EP2198093A1.html> [23 March 2018]

5. Newman, A.P., Nnadi, E.O., Duckers, L.J., and Cobley, A.J. (2011). Further Developments in self- fertilizing geotextiles for use in pervious pavements. *Water Science and Technology* 64 (6), 1333–1339. DOI: 10.2166/wst.2011.180

6. Nnadi, E.O. (2009). An evaluation of modified pervious pavements for water harvesting for irrigation purposes. Unpublished PhD Thesis. Coventry University, UK.

7. Nnadi, E.O., Coupe, S. J., Sañudo-Fontaneda, L. A., and Rodriguez-Hernandez, J. (2014). An evaluation of enhanced geotextile layer in permeable pavement to improve stormwater infiltration and attenuation. *International Journal of Pavement Engineering*, 15 (10), 925-932. https://doi.org/10.1080/10298436.2014.893325

8. Rodriguez-Hernandez, J., Castro-Fresno, D., Fernandez-Barrera, A.H., and Vega-Zamanillo, A., 2012. Characterization of the infiltration capacity of permeable pavements with porous asphalt surface using the CF Infiltrometer. *Journal of Hydrologic Engineering* 17 (5), 597–603. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000480

9. Rodriguez-Hernandez, J., Vega-Zamanillo, A., and Castro-Fresno, D. (2013). Laboratory analysis of the infiltration capacity of interlocking concrete block pavements in car parks. *Water Science and Technology*, 67 (3), 675–681. DOI: 10.2166/wst.2012.614

10. Scholz, M. (2013). Water Quality Improvement Performance Of Geotextiles Within Permeable Pavement Systems: A Critical Review. *Water* 5 (2), 462-479. Doi:10.3390/w5020462

11. Scholz, M. and Grabowiecki, P. (2009). Combined Permeable Pavement And Ground Source Heat Pump Systems To Treat Urban Runoff. *Journal of Chemical Technology & Biotechnology* 84 (3), 405-413. https://doi.org/10.1002/jctb.2054

12. UNESCO, 2008. Asian Pacific FRIEND. Rainfall Intensity Duration Frequency (IDF). Analysis for the Asia Pacific Region. Report from IHP Regional Steering Committee for South East Asia and the Pacific. Edited by Trevor M. Daniell, Guillermo Q. Tabios III.

13. Wardynski, B.J., Winston, R.J., and Hunt, W.F. (2012). Internal Water Storage Enhances Exfiltration and Thermal Load Reduction from Permeable Pavement in the North Carolina Mountains. *Journal of Environmental Engineering* 139(2). http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000626
14. Wilson, S., Bray, B., and Cooper, P. (2004). *Sustainable drainage systems*. (1st ed.). London, UK: CIRIA.
15. Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., and Shaffer, P. (2007). The SUDS manual, no C697. London, UK: Construction Industry and Research Association (CIRIA).
16. Yong, C. F., Deletic, A., Fletcher, T. D., and Grace, M. R. (2008). The Clogging Behaviour and Treatment Efficiency of a Range of Porous Pavements. *11th International Conference on Urban Drainage (ICUD)*. 31st August -5th September, 2008 Edinburgh, Scotland.
17. Park, D., Sandoval, N., Lin, W., Kim, H. and Cho, Y. (2014). A case study: Evaluation of water storage capacity in permeable block pavement. *KSCE Journal of Civil Engineering*, 18(2), pp.514-520.